OP. 3100.102.039 (1)

MINISTRY OF TRANSPORT

RAILWAY ACCIDENTS

# Interim report on the Accidents which occurred on 13th and 17th December 1960 in Glasgow Suburban Electric Trains in the Scottish Region British Railways

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1961

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MINISTRY OF TRANSPORT,
ST. CHRISTOPHER HOUSE,
SOUTHWARK STREET,
LONDON, S.E.
13*th January*, 1961.

SIR,

I have the honour to present for the information of the Minister of Transport, in accordance with the Order dated 20th December, 1960, an interim report on my Inquiry into the accidents which occurred on 13th and 17th December, 1960, in multiple unit trains on the Glasgow suburban electric service in the Scottish Region of British Railways. This service is operated on the dual high voltage A.C. overhead system.

2. In view of the public concern over the withdrawal of the electric trains after the second of these accidents, I have considered it my duty to report as soon as possible the result of the investigations which have led to the establishment of the primary cause of these failures, which was the faulty design of the train transformers, and to announce the action which is being taken to get the electric services restarted. This report therefore deals with these aspects of my Inquiry, and I have included only such descriptive matter as is needed to make my conclusions readily understood. A full report covering all factors affecting these accidents and all other matters relevant to them, whether technical or administrative, will be presented later.

3. I am being assisted in this Inquiry by Mr. F. J. Lane, O.B.E., M.Sc., M.I.E.E., a partner of Messrs. Preece, Cardew and Rider, and a member of the British Transport Commission's panel of Consulting Engineers, who has been requested by the British Transport Commission to make a full and independent investigation, and he has placed his services entirely at my disposal.

4. The first of the two accidents which form the immediate subject of my Inquiry occurred at about 7.9 a.m. on 13th December when, shortly after leaving Renton station, an explosion shattered the equipment compartment in the guard's van of the 7.0 a.m. electric train from Balloch Central to Bridgeton Central. A passenger in the adjacent compartment pulled the communication cord and brought the train promptly to a stand. The guard's compartment was badly damaged and a partition between it and the adjoining passenger compartment was forced in. There was no derailment or fire.

The train carried about 230 passengers, and of these two sustained serious injury and five suffered slight injury or shock. The guard also was seriously injured. All were taken to the Vale of Leven hospital where two passengers and the guard were detained. As soon as the train stopped passengers went for assistance and also informed the driver who took prompt action to protect the train and to report the accident. Police were quickly on the scene, and the first ambulance arrived at 7.30 a.m. The injured passengers were given First Aid and were evacuated to hospital without delay, the last ambulance leaving the scene at 8.0 a.m. The overhead equipment was isolated at 7.40 a.m., the disabled train was drawn back to Alexandria at 10.20 a.m., and normal working was resumed at 11.5 a.m. At the time of the accident the weather was foggy and visibility in the Renton area was only about 150 yards.

5. The second accident occurred at about 1.52 p.m. on Saturday, 17th December. As the 12.45 p.m. train from Helensburgh to Airdrie was leaving Garrowhill station a porter saw white vapour issuing from beneath the rear vehicle, and very soon afterwards the guard, who was travelling in the coach next ahead, heard three bangs and saw clouds of smoke coming from underneath his coach. By means of the train telephone he called to the driver to stop the train. The driver ran back with a fire extinguisher and quickly put out a small fire in the transformer from which the smoke was issuing. The guard went to a nearby signal telephone and advised the signalman who in turn advised the Station Master at Easterhouse. The damaged unit was isolated and the train was worked forward to Easterhouse at 2.10 p.m. where the passengers numbering about 250 were detrained. No one was injured. As a precaution the fire brigade was called at 2.11 p.m.and arrived at 2.23 p.m. Four minutes later the firemen were satisfied there was no fire though some smouldering material was damped out with the aid of one extinguisher. The damaged set was then removed to Heatherya knowe Loop and at 2.50 p.m. normal working on both lines was resumed. It was found that the cover of the transformer had been burst open and was hanging down close to the track.

6. This was the fifth of a series of transformer failures which had occurred since 30th October when a full day's trial was held prior to opening the public service on 7th November. In view of the possible danger which might arise from other failures, the Scottish Regional Management after consulting the British Transport Commission decided to withdraw all electric train services forthwith and not to resume them until the fundamental cause of the failures had been ascertained and the troubles put right.

7. I could not investigate the cause of these two accidents without taking into consideration the other transformer failures which have occurred on the Glasgow suburban system, and also the other troubles which have been experienced in its equipment and which may have had a bearing on the transformer failures. As the investigation proceeded it became essential to check the design of the transformers in use in trains on other sections of British Railways electrified on the high voltage A.C. system to ensure that they were immune from the weaknesses discovered in the transformers on the Glasgow suburban trains. It further became necessary to take note of the failures which have occurred on the other recently opened high voltage A.C. electrified sections of British Railways to ascertain whether they and the transformer failures in the Scottish Region were in any way inter-related and, in particular, whether the introduction for the first time on any railway of a dual high voltage A.C. system had any bearing on the problem.

Mr. E. L. E. Wheatcroft, M.A., M.I.Mech.E., M.I.E.E., a partner of Messrs. Merz and McLellan, another member of the Commission's panel of Consulting Engineers, has been requested by the Commission to make an independent examination of the failures of the traction motors installed by the General Electric Company in some of the multiple unit electric trains running on the Eastern Region suburban service. Mr. Wheatcroft has promised me every assistance, and he and Mr. Lane have agreed to collaborate to ensure that all aspects of the subjects under investigation are covered.

8. The first stage of the Glasgow suburban electrified system covers the lines to the north of the River Clyde from Helensburgh in the west through Glasgow Queen Street (Low Level) station to Airdrie in the east. There are branches to Balloch, Milngavie, Bridgeton Central and Springburn. On the Helensburgh route both the direct line via Westerton and the Clydebank branch via Yoker are electrified.

The outlying lines are electrified on the 25kV 50 c.p.s. single phase A.C. overhead system, but on account of the restricted clearances of the tunnels and bridges in the inner suburban area, the overhead equipment on the lines through this area is energised at 6·25 kV. Altogether some 31 route miles are energised at 25 kV and 20 miles at 6·25 kV. The total electric single track mileage is 116.

9. As I shall describe later, the train equipment is designed to operate on either voltage and the change-over is carried out automatically. A neutral section divides each 25kV line from the adjoining 6·25kV line, and ground magnets, placed at suitable positions in the track adjacent to the entrance to and exit from the section, operate relays in the train equipment. These ensure that power is cut off from the unit before it enters the neutral section, that the transformer connections are set to receive the appropriate voltage and that power is not switched on until the unit, having passed the neutral section, is correctly connected for the new voltage. Other neutral sections are provided in the 6·25kV area to avoid paralleling the two different phases of the supply system and similar controls are provided except that the change-over switch in the equipment is not operated because there is no change of voltage.

Change-over of voltage takes place near Westerton on the main line and near Dalmuir Park on the line from Helensburgh, and near Parkhead Junction on the Airdrie line. The neutral sections on the 6.25kV system are at Finnieston between Partick and Charing Cross and near Yoker on the line from Helensburgh.

10. Power is supplied from the 132kV systems of the South of Scotland Electricity Board and the North of Scotland Hydro-Electric Board. It is stepped down to 25kV single phase for distribution to the overhead traction system. The supplies from the South of Scotland Board are taken at feeder stations at Parkhead and Coatbridge on the Airdrie line, and from the North of Scotland Board at a feeder station at Dalreoch which is the junction for the Balloch branch on the Helensburgh line. Supplies for the 6.25kV lines are obtained from the 25kV supply through further step-down transformers provided by the railway in subsidiary feeder stations at Westerton, Finnieston and Dalmuir Park and through similar transformers installed at the Parkhead feeder station.

11. Track section cabins with sectioning switches and circuit breakers are provided where necessary. Booster transformers are installed to limit the magnitude of induced voltage in neighbouring parallel conductors such as telecommunication and signalling cables. These equipments will be described in more detail in the final report.

*General description*

12. The Glasgow multiple unit trains are made up of 3-car units each comprising a driving trailer at the ends with a motor coach in the middle. The motor coach has a motor on each axle, and it carries the pantograph, mounted above the guard's van. The power equipment is carried below the floor of the coach, but the low tension (L.T.) switch gear and some other auxiliary equipment is in a closed compartment between the guard's van and the passenger compartment. Each trailer has a driving cab at one end, and one of the trailers carries the train lighting battery with its charging equipment and the air compressor for charging the braking system. The coaches were built by the Pressed Steel Company, Ltd., and the electrical equipment was supplied by Associated Electrical Industries (Manchester) Ltd. This company is referred to as A.E.I. throughout the remainder of the report.

The current from the overhead contact wire is collected by the pantograph and after passing through an air blast circuit breaker on the roof it is carried through heavily insulated cables to the transformer which is mounted between the main members of the underframe in the centre of the vehicle.

The transformer which weighs about 4 tons has a rating of 970 kVA and it is designed to take current through the primary winding either at 25kV or 6.25kV. The secondary winding has a rated voltage of 2,770 volts and the tertiary 273 volts. The current from the secondary winding is taken to four single anode pumpless air-cooled mercury arc rectifiers, each with a continuous rating of 700 kW at 1,950 volts D.C. output.

Each pair of traction motors is fed through an iron-cored smoothing choke which is designed to limit the A.C. ripple in the D.C. motor current to 30 per cent. at the continuous rating. The two chokes for the four motors are mounted together in a tank on the underframe and they are cooled by the same cooling system as the main transformer.

*The motors*

13. The 210 h.p. motors are axle-hung with nose suspension. They have been designed to operate on a rectified supply of 975 volts with a current of 165 amps with full field and 180 amps with weak field.

*Auxiliary equipment*

14. The auxiliary equipment includes the oil pump and radiator fan for the transformer oil-cooling system and the rectifier fans, all working directly off the tertiary A.C. supply; also the main air compressor and the auxiliary air compressor, both operated by D.C. motors supplied through an independent rectifier from the tertiary A.C. winding.

*The transformer*

15. The primary winding of the transformer comprises a cylindrical coil wound in four sections; they are connected in series for 25kV and

in parallel for 6.25kV. An electro-pneumatic operated change-over switch is mounted in an oil-filled chamber at one end of the transformer; this vessel does not form part of the oil circulating system but it is vented to the conservator tank through the same pipe that vents the transformer cooling oil. The change-over switch is of the "off-load" type and it is operated by relays which respond either to the 25 or to the 6.25kV supply.

The secondary winding is laid in four layers, or coils, one on top of the other with appropriate oil passages round the central laminated steel core. It is provided with seven intermediate tappings of which one is the mid-point; all are designed to carry full load. The tap changer and the contactors are mounted in a cabinet fixed to the underframe. The tertiary winding comprises two coils in series; one at each end of the primary winding.

### *Oil circulating system*

16. The whole transformer is encased by a fabricated steel tank, 2 ft. 10 ins. high, 2 ft. wide and 6 ft. 4 ins. long, which is mounted horizontally with the cover plate at the bottom. It is immersed in oil which is circulated at a rate of 50 g.p.m. The oil circulating system embraces not only the transformer but also the tank in which the smoothing chokes are mounted. The oil pump is attached to this tank from which it sucks the oil and forces it into the top of the transformer tank. After passing through this tank the oil is drawn through the air-cooled radiator to the choke tank. Thus part of the system is under a negative pressure having a maximum of about −6 lbs. p.s.i in the choke tank. In the transformer tank the oil is under a positive pressure rising to a maximum of about 3 lbs. p.s.i.

### *The conservator tank*

17. A conservator tank is mounted in the equipment compartment in the guard's van and it is connected to the top of the transformer tank by a ½ in. diameter pipe. Its purpose is to keep the transformer full of oil and to take up variations in oil level due to temperature variations which may range from 0° C. or even lower in the winter to 95° C. when the oil is heated to its maximum permissible temperature in summer. Originally the tank was vented to atmosphere through a silica-gel breather but as will be explained later this arrangement was changed after the first transformer failure.

### *The auxiliary equipment compartment*

18. The auxiliary equipment compartment is at the passenger saloon end of the guard's van. It is 18 ins. deep and it extends for the width of the coach. In addition to the conservator tank it houses the low tension (L.T.) cupboard, containing L.T. fuses, cut-out switches, some fault indicators and relays, and a proportion of the auxiliary contactors and relays. The operating gear of the circuit breaker projects into this compartment and the auxiliary compressor and certain compressed air apparatus for pantograph and circuit breaker operation are housed in it.

*Motorman's controls*

19. The motorman's controls are extremely simple. They comprise a main motor control handle incorporating a dead man's feature, the reversing handle and the combined brake controller for operating the electro-pneumatic and Westinghouse automatic air brakes.

The main motor controller handle has four notches in addition to the 'off' position, namely:—

1. Shunt.
2. Half voltage.
3. Full voltage.
4. Weak field.

An indicator is lighted in the driver's cab whenever the pantograph is in contact with an energised overhead contact wire. The fault indicators, however, are in the guard's van.

The motorman and guard can speak to each other by telephone.

*Protection*

20. The protection comprises certain electrical relays, and also other devices intended to ensure the adequate cooling of the transformer and associated equipment and to maintain appropriate temperatures in the rectifiers.

The electrical devices include a relay which cuts off power by tripping the air blast breaker in a variety of fault conditions and Metrosil non-linear resistance units which discharge over-voltage from parts of the equipment, including the rectifiers and individual parts of the transformer secondary winding.

The other devices include a thermostat which protects against overheating of the cooling oil and a low oil-level relay, both of which cut off power by opening the air blast circuit breaker.

The functioning of these and other protective devices will be discussed in my final report.

## THE TRANSFORMER FAILURES

*The explosion in Unit* 003 *on* 30*th October*

21. The first transformer failure occurred on Sunday, 30th October, during a full scale rehearsal of the new week-day electric public services in order to familiarise staff to the new conditions prior to opening for public service on 7th November. A similar rehearsal had been carried out on the two previous Sundays without incident, but on the 30th October an explosion occurred in the equipment compartment of the guard's van of a 6-car train immediately after it had stopped at Charing Cross station at about 6.25 p.m. The guard's van and the adjoining passenger compartment were damaged but no one was injured. The cause of the explosion was traced to a mixture of oil vapour and air having become ignited in the equipment compartment, probably by a spark from a contactor in the L.T. cupboard.

It was found that the secondary winding of the transformer had become seriously overheated and that as a result, the circulating oil had vaporised and entered the conservator tank whence it was not able to escape rapidly;

consequently the pressure in the tank built up until the cover lifted slightly and allowed the vapour to enter the equipment chamber. The transformer tank also was bulged and the cover was sprung by the vapour pressure inside it.

It was later found that a ½ in. vent pipe from the conservator tank was restricted to ⅛ in. diameter in the silica-gel breather. To rectify the defect the breather was by-passed and a 1 in. diameter vent pipe was fitted to a plug hole at the top of the tank. The pipe should have been taken through the floor to vent direct to atmosphere, and it was accepted that this would provide an ample opening through which any oil gases could escape should trouble be experienced with another transformer. However, the contractor who carried out the alteration connected the 1 in. pipe to the existing ½ in. pipe through the floor thus reducing the vent exit to the size of the pipe between the transformer and the conservator tank.

### *The Failure of Unit* 042 *on* 14*th November*

22. Whilst a 6-car train was running into Queen Street from Partick at about 5.35 a.m., the driver experienced loss of power. He reset the breakers both here and again at High Street and Bellgrove. He still could not obtain full power and he travelled slowly to Airdrie, and it appeared that one unit was pushing the other. At Airdrie the driver was instructed to return the train to Dalmuir Park where it was taken out of service. It was found that the transformer tank of Unit 042 was bulged and the cover was sprung so that oil was leaking from it. There was no explosion in the guard's van nor any sign of leakage from the conservator tank. The secondary winding of this transformer was also found to be badly overheated and it was considered that the larger vent in the conservator tank had functioned effectively and had enabled the oil gases to escape safely to atmosphere, thus preventing an explosion.

### *The Explosion in Unit* 051 *on* 13*th December*

23. On 13th December an explosion occurred at about 7.9 a.m. near Renton, as already described. It was clear that in this case the enlarged vent had not been big enough to allow the oil gases to escape before pressure in the conservator tank bulged the cover and allowed vapour into the equipment chamber where it exploded with results very similar to those on 30th October. Immediate steps were taken to improve the ventilation in the equipment chamber by cutting holes in the roof and floor. A $\frac{3}{16}$ in. washer was inserted in the pipe leading from the transformer to the conservator tank so as to restrict the flow of gas should another transformer overheat. Railwaymen and contractor's men worked throughout the night of 14th/15th December under the most adverse weather conditions to carry out this work, and by 4.0 a.m. on 15th December, 44 sets had been modified out of a total of 50 required for a full service. This resulted in some cancellation of trains because no unmodified set was allowed into service. It was considered that these alterations would prevent effectively the formation of an explosive mixture of oil vapour and air in the equipment chamber should another transformer overheat, and that all the danger to the passenger compartment and the guard's van was removed. It was realised, however, that the possibility of a transformer overheating still existed.

*The failure of Unit* 031 *on* 14*th December*

24. At about 2.45 p.m., as the 1.45 p.m. 6-car train from Helensburgh to Airdrie was entering Carntyne station, the guard noticed smoke coming from the leading set. He thought that the transformer was on fire and called to the driver to drop the pantograph and come to his aid. The driver saw volumes of smoke pouring from the transformer of the leading Unit 031 and turned an extinguisher on it. Meanwhile the guard ordered the passengers to detrain, after which the defective set was taken out of service and the rear set continued working as a 3-car train. The transformer tank of Unit 031 was found to be bulged also and oil was leaking from it when examined later in the day. The enlarged vent had been fitted to the conservator tank but not the other modifications which would have been put in that night. On this occasion also the vent had allowed the oil vapour to escape before an explosive mixture could build up in the equipment chamber.

*The accident to Unit* 014 *on* 17*th December*

25. At about 1.52 p.m. on Saturday, 17th December, the accident occurred near Garrowhill, as already described. It was found that the cover of the transformer had been burst open and was hanging down close to the track. Although the modifications carried out on 14th December had prevented an explosion in the guard's van, the pressure in the transformer itself had built up so rapidly that the oover bolts had sheared before the gas could escape through the vent pipe. The possible danger of damage to carriage equipment and the track was such that the Scottish Regional Management, in consultation with the British Transport Commission, decided during the early hours of Sunday morning to withdraw the electric trains from public service immediately—a decision about which I was consulted beforehand and with which I entirely agreed.

### TRIAL AND SERVICE RUNNING

26. On 8th July, 1957, the Metropolitan Vickers Electrical Company, Ltd., which is now the A.E.I. (Manchester) began experiments with an A.C. high voltage multiple unit set on the Lancaster-Morecambe-Heysham overhead electrified line which is energised at 6,000 volts 50 c.p.s. single phase A.C. As a result of the experience gained on this line the equipment was designed for the Glasgow suburban trains and on the 18th June, 1959, the first of these trains began trial running in the London Midland Region on the Styal line which is energised at 25 kV 50 c.p.s. single phase A.C. The first section of the Glasgow suburban overhead equipment to be completed was the Milngavie branch energised at 6·25 kV and trial running began on this line in May, 1960. As other sections of the electrification were completed trial running was extended and continued up to the opening of the public services on 7th November, 1960.

The total mileage run up to the closure of service on 17th December was:—

| | |
|---|---|
| Trial running ... ... ... ... | 145,865 miles |
| Service running ... ... ... ... | 335,388 ,, |
| Total ... ... ... ... | 481,253 ,, |

The mileage run by the units on which the transformers failed was :—

| *Units* | *Trial running* | *Service running* | *Total* |
|---|---|---|---|
| 003 | 3,939 | — | 3,939 |
| 042 | 3,179 | 1,321 | 4,500 |
| 051 | 1,414 | 6,200 | 7,614 |
| 031 | 1,713 | 5,865 | 7,578 |
| 014 | 2,524 | 4,359 | 6,883 |

## THE TECHNICAL INVESTIGATIONS

### *Examination of Unit* 003

27. Unit 003 in which the explosion took place on 30th October was returned to Hyndlands Depot where it was examined by the late Mr. J. J. Finlayson, the Chief Mechanical and Electrical Engineer, and Mr. A. Watt, the Electrical Engineer, both of the Scottish Region. In view of the serious nature of the failure, Mr. J. A. Broughall, the Electrical Engineer (Development), British Transport Commission, went to Scotland and examined the equipment with representatives of A.E.I., the manufacturers. The transformer was removed from its tank and it was found that, although the primary winding was in good condition, the secondary winding had been severely burnt, part of the windings had fused and the coils were badly distorted. It was thought that the damage was caused by a failure of the oil circulating system which resulted in the winding overheating to such a temperature that the oil was vaporised and the insulation was burnt. The transformer was returned to the maker's works at Wythenshaw for further investigation.

### *Examination of Unit* 042 *on* 14*th November*

28. Whilst the investigations into the cause of this accident were in progress, the second failure occurred in Unit 042 on 14th November. A further meeting of the B.T.C., Scottish Region and A.E.I. Engineers was held in Glasgow on 16th November, and Mr. H. W. Hardern, A.E.I. Transformer Engineer, stated that the condition of the transformer in this unit was very similar to that in Unit 003, and he gave his opinion that the damage had been caused by overheating over a long period rather than by an instantaneous fault. It was suggested that the overheating was due either to the failure of the cooling system or to overloading over long periods. In order to obtain further evidence, this transformer and four others were sent to the A.E.I. Works at Wythenshaw for detailed examination. The units selected and the reason for their selection were:—

001. Had been in service for the longest period and had suffered from control gear failures.

033. Had been subjected to over-voltage on at least three occasions.

036. Had assisted defective units on several occasions and might therefore have been subjected to overload.

041. Had run without trouble.

### *Meeting on* 19*th November*

29. A further meeting of the B.T.C. and A.E.I. Engineers was held at Wythenshaw on Sunday, 19th November, to examine and discuss the state of the transformers which had been returned from Glasgow. The primary

winding was removed from each of the undamaged transformers but there were no signs of overheating on either the primary or secondary windings. The meeting agreed unanimously that the complete disappearance of the secondary insulation on both the failed transformers and the absence of any sign of overheating on the four other transformers, indicated that the failures were due to prolonged overheating of the paper insulation and almost certainly from a failure of the oil circulation through the secondary winding.

In the course of the discussion the electrical and thermal characteristics of the primary and secondary windings and of the chokes were compared; they were found to be sufficiently different to explain why neither the primary nor the chokes had suffered damage from overheating.

*Meeting on 24th November*

30. Another meeting was held on 24th November at which the A.E.I. Engineers suggested that it was possible for an air lock in the system to have stopped the pump from circulating oil and they undertook to set up in their works a transformer unit complete with oil circulating system and to subject it to comprehensive tests.

*Meeting on 1st December*

31. On 1st December the B.T.C. and A.E.I. Engineers met again at Wythenshaw to consider the results of the oil circulating tests. Admission of air to the system had not stopped the oil flow but had reduced it to about one quarter of its normal flow of 50 g.p.m. Further tests were arranged and it was agreed to put in hand some minor modifications to the circulating system, pending completion of these tests.

*Meeting on 14th December*

32. On 14th December following the explosion on the previous day, an urgent meeting of the B.T.C., Scottish Region and A.E.I. Engineers was held in Glasgow at which I was present. At that time the opinion still was held that the transformer failures were the result of the stoppage or restriction of the cooling oil, and the hope was expressed that a solution would be found by the week-end since further extensive tests were in progress at Wythenshaw. It was decided as a matter of urgency to make the changes described in paragraph 23, pending a solution of the major problem.

*Meeting on 18th December*

33. The accident on Saturday, 17th December, led to the withdrawal of the Glasgow electric service and on Sunday morning a meeting was held at B.T.C. Headquarters at which the B.T.C. Electrical Engineers met the Electrical Engineers of the other Regions and of the three manufacturers who had built transformers for the multiple unit trains, namely A.E.I., the General Electric Company and the English Electric Company. I also was present as well as Mr. J. Ratter, a Member of the Commission, and Mr. R. C. Bond, the Commission's Technical Adviser.

Mr. Broughall gave a short history of facts leading up to the meeting. Mr. F. Whyman, the General Manager, Traction Division, A.E.I., who had been present at the earlier investigations stated that the preliminary tests and running had not disclosed any weakness either in the transformer or the circuits, and it was not until full scale service running took place that the troubles developed. He could not at that time give any satisfactory explanation of the cause of the secondary windings burning out. In all the cases the oil pumps had been working satisfactorily after the failures and so far none of the tests carried out at Wythenshaw had resulted in stopping oil circulation completely. With oil flow reduced to one quarter of its full rate, the temperature rise of the secondary winding reached a steady value of 65°C. which was well within the specified maximum rise of 75°C. With oil flow stopped the following rises were recorded:—

| | | |
|---|---|---|
| After 10 minutes | ... ... ... ... ... ... | 41°C. |
| „ 15 „ | ... ... ... ... ... ... | 54°C. |
| „ 25 „ | ... ... ... ... ... ... | 69°C. |

A current of 321 amps was applied throughout this test. Mr. Whyman was asked to arrange further tests up to a maximum temperature possible without destroying the insulation of the secondary winding.

Mr. Whyman thought that one possible cause of overheating was the operation of a 6-car train with only two motors working. He had heard from his staff that this had occurred on at least one occasion and he thought it might be a contributory cause. Arrangements were made to carry out tests in Scotland and check this theory. (These tests though not conclusive did not appear to support this theory.)

Mr. Hardern said that oil would tend to vaporise at approximately 180°C. and that the paper insulation would begin to char at about 150°C. He restated his opinion that the windings had been subjected to temperatures of this order for some considerable time and that the general overheating did not point to any of the windings having failed or having been short circuited externally.

The oil circulating system was examined and it was agreed that a negative pressure in the choke might cause vaporising of the transformer oil and produce pockets of vapour which could arrest the oil flow. Mr. Hardern undertook to investigate this forthwith.

During an interval in the meeting I discussed with the B.T.C. officers the desirability of appointing a consulting engineer to make an independent investigation, and they decided to ask Mr. F. J. Lane, a partner of Preece, Cardew and Rider, to undertake this work.

Finally it was agreed to continue the discussions with the A.E.I. Engineers at Wythenshaw on Wednesday, 21st December, prior to the opening of my Inquiry in Glasgow on the following day. Mr. Lane would be asked to attend.

### *Meeting on 21st December*

34. On 21st December in company with Mr. Lane, Mr. Bond, Mr. S. B. Warder, Chief Electrical Engineer of the B.T.C. and Mr. Broughall, I met the Officers and Engineers of A.E.I. Manchester. The morning was spent in examining the transformers Nos. 003, 042, 051 and 014 which had been damaged as a result of the failures on 30th October, 14th November, 13th December and 17th December respectively. All presented similar features.

The primary windings were virtually undamaged but the secondary windings had all been extensively overheated. The paper insulation appeared to be completely burnt away from the outer coils, some of the turns had fused and they had been very badly distorted.

*Examination of Unit* 031 *on* 21*st December*

35. In the afternoon of 21st December the transformer from unit No. 031 which had failed on 14th December was stripped down in our presence. The tank had been badly distorted but again the primary winding appeared to be in good order and when this winding was lifted it was noted that the wrappings covering the secondary winding were undamaged. On removing them it was seen that the outer coil No. 4 of the secondary winding was distorted but there were no signs of the insulation burning and some oil was still noticeable.

A hole was found in coil No. 3, however, and it extended back to the core. Coil No. 2 was badly burnt, especially near the middle of the winding where an area covering 20 turns and extending over about one-fifth of the circumference had fused. In coil No. 1 a larger area had fused and some of the turns below it were distorted and some were burnt. The distortion was similar in character to that of the secondary windings of the other damaged transformers but not so severe.

The absence of general overheating and the localised burning of the coils provided evidence for the first time that the thermal theory could probably be discounted and that the failure was due to a breakdown of the winding insulation from other causes.

*Examination on* 22*nd December*

36. During my Inquiry in Glasgow on 22nd December I was informed that two other transformers in units Nos. 030 and 049 were "suspect" and accordingly in company with Mr. Lane, B.T.C. and A.E.I. engineers I inspected them that evening. Neither transformer showed outward signs of distress but in view of the discovery that had been made on the previous afternoon, it was decided to send both to Wythenshaw for examination.

*Examination of Unit* 030 *on* 28*th December*

37. The two suspect transformers arrived at Wythenshaw on 27th December and unit No. 030 was examined by Mr. E. F. C. Masters, one of Mr. Lane's engineers, the next day. It had failed in service owing to the rise in the oil temperature having operated the thermostat which tripped the circuit breaker. The fuse in the circuit of the oil pump had blown and stopped it from working, consequently it was thought that the trouble with this transformer was simple overheating of the circulating oil. However, when the primary winding had been removed, the outer coil of the secondary winding showed serious displacement of the turns and overriding in 10 places but no signs of overheating. "Scuffing" of the paper insulation had occurred where the overriding of the turns had taken place. The winding of coil No. 3 was distorted particularly at the top, but there was no overriding. The winding of coil No. 2 also was slightly distorted with no overriding, and on coil No. 1 there was very slight distortion. None of these inner coils showed any sign of overheating.

This transformer was clearly in the early stages of secondary winding failure and a breakdown of the insulation between the overriding turns would undoubtedly have followed if the transformer had remained in service. Its condition with its distorted secondary winding and overriding turns indicated that it had been subjected to severe electro-magnetic forces which it could not withstand. The lack of any sign of overheating of the windings still further discounted the theory that failure of the oil circulation was a primary cause; in fact, the thermostat had operated before the temperature of the oil had risen to a dangerous value.

*Meeting on 1st January*

38. Attention was therefore concentrated on the electrical rather than the thermal problem, and Mr. Lane and Mr. Broughall returned to Wythenshaw on Sunday, 1st January, for another meeting with the A.E.I. engineers.

It was agreed at this meeting that the secondary windings of the transformers were not strong enough to withstand the severe electro-magnetic forces to which they had been subjected, and they would have to be redesigned. The high voltage winding on the other hand appeared to be satisfactory.

As I shall describe in my final report there was a period when there were frequent rectifier backfires and some failures of the control gear which would subject the transformers to short circuit conditions. It was considered that these conditions and the backfires in particular were sufficient to account for the displacement of windings by electro-magnetic forces. The possibility of over-voltage and overheating could not be entirely ruled out as contributory causes.

Mr. Whyman made suggestions for modifying the transformers to increase their strength, and for altering the circuits to reduce the forces acting on the windings. He also proposed to improve the oil cooling system. He said he would put forward definite proposals as soon as they could be formulated.

It was planned to carry out at the Switchgear Testing Company's Testing Station a series of tests largely to evaluate the extent and the effect of over-voltage conditions. A 3-car set had been sent from Glasgow for testing immediately after my Inquiry on 23rd December and this was used as well as an independent transformer.

Arrangements were also made to re-inspect transformers Nos. 001 and 036 to see whether, in the light of the further knowledge which had now become available, either of them gave any evidence that the windings had been deformed by electro-magnetic forces. It will be recalled that at a previous examination, both these transformers had been considered satisfactory (see paragraphs 28 and 29). It was also decided to inspect transformer No. 049 (see paragraph 36).

*Meeting on 7th January*

39. On Saturday, 7th January, in company with Mr. Lane, Mr. Warder and Mr. Broughall, I returned to Wythenshaw for a further meeting with Mr. H. West, Managing Director, A.E.I., and the Officers and Engineers of A.E.I. (Manchester).

First we inspected transformers Nos. 001, 036 and 049 and photographs of some of the coils which had been removed at our request. All the primary windings were in good condition and the secondary winding of No. 001 showed no sign of deformation. There was some very slight distortion of the secondary windings of No. 036 and No. 049 ; some of the turns on coil Nos. 4 and 3 of No. 049 were slightly proud and showed a tendency to override.

At the meeting which followed, the A.E.I. Engineers gave the results of their over-voltage tests. They were not conclusive but they did not suggest that over-voltages had contributed materially to the failures.

The new proposals for the modification of the transformers were accepted in principle, subject to some further prototype tests, and arrangements for rebuilding all the Glasgow transformers and carrying out all other necessary modifications, including alterations to the transformer oil cooling system, were discussed. A joint working party of B.T.C., Scottish Region and A.E.I. Engineers was set up to formulate proposals.

Mr. West said that the resources of both the A.E.I. Manchester and Rugby Works would be utilised in order to complete the work in the quickest possible time. It was agreed that no advantage would be gained by calling on the productive capacity of other manufacturers. It was decided to hold a further meeting in London on 11th January to finalise the transformer design and confirm the rebuilding programme.

*Meeting on 11th January*

40. At the meeting on 11th January the design of the modified transformer was discussed and accepted in principle by Mr. Lane and the Commission's Engineers. A brief description of its salient features is given in my Remarks which follow. A programme for the rebuilding of the transformers was agreed and arrangements for carrying out this work and the other modifications were settled. I make further references to these in my Remarks.

*Meeting on 12th January*

41. A meeting between the British Transport Commission Engineers, their Consulting Engineers and the Manufacturers of all types of transformer used in multiple-unit trains was held on 12th January to consider matters of common interest arising out of the transformer failures. I was present and shall comment on these in my final report.

*Examination of other transformers*

42. During their visit to Wythenshaw on 1st January, Mr. Lane and Mr. Broughall examined a transformer of the type used in the Eastern Region multiple unit trains which have been converted from D.C. to A.C. traction. On the previous day they had been to Birmingham where they examined the General Electric Company's transformer which is in use on some of the Eastern Region suburban trains which were built for A.C. traction, and on 2nd January they saw at Stafford one of the English Electric Company's transformers which is also used in other Eastern Region suburban trains. Finally on 4th January they inspected an A.E.I. (Rugby) transformer similar to those installed in the London Midland Region multiple unit electric trains now running between Manchester and Crewe.

There were such differences in the design and construction of these transformers and their associated equipment that Mr. Lane considered there was no danger of a repetition of the Glasgow failures, but he felt it would be desirable to arrange a further series of tests. Particulars of these differences will be included in Mr. Lane's final report to the British Transport Commission.

*Action on other Regions as a result of the accidents to the Glasgow suburban electric trains*

43. The British Transport Commission inform me that all the A.C. multiple unit trains have basically similar equipment, but in addition to variations in the construction of transformers, there are other deliberate variations in components such as rectifiers, circuit arrangements and control gear, from which it was intended later to make a seleotion. Among these variations were different arrangements of the transformer cooling and venting systems. The mounting of the conservator and certain other equipment in a compartment in the guard's van, substantially as described in paragraphs 17 and 18 above, was, however, a common feature.

Notwithstanding that only one other transformer failure had occurred in some 200 transformers of four other kinds in service, Mr. Broughall on his return from his visit to Glasgow on 1st November arranged a further investigation between the British Transport Commission and the Contractors' Engineers of the oil cooling and venting arrangements in all types of A.C. train. On 3rd November Mr. Warder gave instructions for increased vents to be provided between the conservator and atmosphere in certain cases. This work was completed by 5th November.

After the explosion on the 13th December, despite the fact that no further transformer failure had occurred on other Regions, orders were given immediately for additional ventilation to be provided in the equipment compartments of the guards' vans for all A.C. trains. This has been done. Plans were also to be prepared for removing the conservator from the guard's van though this was not considered essential for safety. This matter is now one of those being examined by Mr. Lane in consultation with all concerned.

## CONCLUSIONS AND REMARKS

44. All the preliminary investigations were based on the belief that severe and prolonged overheating was the primary cause of the transformer failures. The examination of transformer No. 031 on 21st December threw the first doubts on this theory and suggested that the insulation might have failed from other causes. The condition of transformer No. 030 which was first inspected on 28th December confirmed this doubt and showed how the insulation of the secondary winding could be broken down. The serious distortion of the outer coils and overriding of the turns would have led to the breakdown of the paper insulation ; the first signs were evident from the "scuffing" of this insulation on the turns which had overriden. Once the insulation broke down severe arcing would occur, followed almost immediately by the "cracking" of the oil and the rapid build-up of gas pressure in the transformer tank. The distortion of the coils of the secondary winding of this transformer also indicated that they had been subjected to severe electro-magnetic forces

which they could not withstand. The examination of transformers Nos. 036 and 049 on 7th January indicated that they had also been subjected to forces of this kind, but they had suffered much less coil displacement.

45. As already mentioned, Mr. F. J. Lane, Partner of Messrs. Preece, Cardew and Rider, who has been assisting me in this Inquiry, is a member of the British Transport Commission's panel of Consulting Engineers, and he was requested by the Commission to make an independent investigation into the failures which have occurred on the Glasgow suburban multiple-unit electric trains. He has made an interim report to the Chief Electrical Engineer of the British Transport Commission in which he sets out his views on these failures and his opinion on the design of the transformers used in other multiple unit trains. I accept his report which is as follows:—

## INTERIM REPORT ON MULTIPLE-UNIT TRANSFORMER FAILURES

"Since your request on December 19, 1960 for an independent investigation and report, our examinations and discussions, in co-operation with the B.T.C. staff and the manufacturers, have been pressed forward with the object of determining the reasons for the transformer failures and of initiating a reconstruction programme at the earliest possible date. A definite stage has now been reached at which, although there are still a number of lines of investigation which must be followed through, an interim report seems appropriate for action and information.

It is now agreed that, on the transformers supplied by A.E.I. (Manchester) for the Glasgow suburban electrification, the secondary winding assemblies are not strong enough to support the conditions to which they have been subjected in service operation.

It is well known that transformers operating in association with mercury arc rectifiers are liable to experience onerous current and voltage conditions due principally to occasional back-fires in the rectifiers (equivalent to direct short circuits) and to current chopping which gives rise to over-voltages. The magnitude and frequency of these effects will vary with the different designs of circuit and apparatus but it is generally recognised that one important feature in the design of the transformer is the provision of extra strength in the winding structure to withstand the electro-magnetic forces of heavy current conditions.

In the early stages of public service in Scotland, the A.E.I. rectifiers are reported to have suffered back-fires on numerous occasions as a direct result of overheating due to defective ventilating arrangements. Failures of control gear had also caused short circuits, mainly during trial running. The manufacturers have stated that they are satisfied that the magnitude and frequency of these occurrences were sufficient to account for the winding failures and we accept this as reasonable. The difficulty with the ventilating equipment was corrected, and during the last weeks of service the performances of the rectifiers was good. Correction of the control gear faults was in hand when the service was closed. Nevertheless it is accepted that the design of the transformer secondary winding is inadequate to withstand the heavy currents which must be encountered occasionally in regular service.

Transient over-voltages (often referred to as surges) are always a possible source of trouble in any electric circuit, and some such voltages have been detected during the tests reproducing certain service conditions. We are satisfied that the breakdown of the winding insulation has not been initiated by such voltages but we are continuing our investigations into the origins and possible effects of these over-voltages to ensure that the circuit safeguards are adequate.

No evidence has yet been submitted to us to indicate that the failure of these transformers is due to any special conditions arising from the dual high voltage A.C. electrification system.

A modified transformer design has been accepted in principle and details are now being prepared. Prototypes will be subjected to short-circuit and other tests. Preparations for substituting the modified transformers for existing units are actively in progress. We are also continuing our examination of the means provided for detecting and clearing incipient troubles in the transformer and associated equipment.

In the light of experience gained in the examination of the transformers which failed in Glasgow, an inspection has been made of the multiple-unit transformers provided for A.C. electrification in other Regions. These include transformers manufactured by A.E.I. (Rugby) for Manchester/Crewe trains, by A.E.I. (Manchester) for the converted direct current trains on the Liverpool Street-Shenfield-Southend lines, by G.E.C. at Witton for the Enfield-Chingford-Bishop's Stortford line trains, and by the English Electric Co. Ltd. at Stafford for trains to be used later on the London, Tilbury and Southend line but now working with the other Eastern Region multiple-unit trains. Certain of these transformers had been subjected to short-circuit conditions but, except for one A.E.I. (Rugby) unit, none has failed in service or has exhibited any signs of winding displacement similar to those found in Glasgow. The single Rugby unit had been subjected to abnormally severe treatment, the originating cause of which has been corrected, and we are satisfied that, having regard to the design features, to the particular circuit conditions, and to the performance of similar units, there is no cause for concern. All other designs are thus considered to be suitable to continue in service but, in order to remove any doubt, all types will be subjected to further tests when a suitable programme has been agreed."

F. J. Lane,  
For Preece, Cardew & Rider.

46. The transformer supplied by A.E.I. (Manchester) for the Glasgow multiple-units trains was well built of high quality materials. It had passed all the tests laid down by the Commission including the appropriate requirements of British Standards.

However, as explained above, the design did not provide sufficient strength for the secondary winding to resist the very heavy electro-magnetic forces which could be applied under the arduous conditions of electric traction.

47. The transformer has now been re-designed. It will be made up of a series of "pancake" coils of primary and secondary windings, interspersed in suitably disposed groups. The turns in each coil of the secondary winding will be of stronger construction than those in the original winding.

48. As mentioned by Mr. Lane, the difficulty with the ventilating equipment of the rectifier has been corrected and the faults in the control equipment are being put right. Thus the chief causes of the trouble have been eliminated, but under service conditions of electric traction occasional short circuits, back-fires and motor flash-overs must be expected and the equipment must be designed to cope with them. Consequently, additional reactance will be included in the circuits to limit these abnormal currents, and additional arrangements will be made to limit the effect of voltage surges and to protect the circuits fed from the tertiary winding.

Thus the forces acting on the transformer windings will be greatly reduced and their mechanical strength greatly increased. It can therefore be stated that the modified transformer will withstand the electro-magnetic forces and voltage surges which may be applied to it in service. It will, however, be given a new series of rigorous tests under Mr. Lane's direction to prove its reliability before public services are resumed with the modified equipment.

49. In addition to re-designing the transformer all the modifications found necessary as a result of the experience gained in trial and service running will be carried out. These will include the alteration of the transformer oil system. The disposition of the pump will be changed so that the smoothing choke tank and radiator, like the rest of the system, are under a slight positive instead of a negative pressure. The size of the vent pipes from the transformer to the conservator tank and to atmosphere will be increased and, although not essential for safety, the conservator tank will be removed from the equipment compartment in the guard's van and placed on the outside of the coach.

50. The execution of all this work will be a formidable task. It will require the concentration of all the motor coaches of the Glasgow multiple-unit trains in selected workshops where the transformers and other equipment can be taken down for modification. The transformers will be sent to the Manchester and Rugby works of A.E.I. whose Managing Director, Mr. H. West, has assured me that the full resources of these two factories will be used to ensure that the transformers needed for the full public services will be rebuilt at the fastest possible rate. The rebuilding of the transformers needed for the trains to work the second stage of the Glasgow electrification will follow. The first units to be completed will be given thorough running trials before public services are resumed. Although it is expected that trial running will begin during March, it is not possible at this stage to give a forecast of the date on which public services can be started, but it seems likely that the work may take a few months to complete.

51. Although as I have stated in the opening of this report I had intended to confine my remarks to establishing the primary cause of the Glasgow transformer failures and the action taken to get the services restarted, I consider it desirable to make reference to the failures which have occurred on the Eastern Region in the multiple-unit stock equipped by the General Electric Company and which I am now investigating, as already explained in paragraph 7 of this report. On Sunday, 8th January, I attended a

meeting between the British Transport Commission's Engineers, Mr. E. L. E. Wheatcroft, Partner of Messrs. Merz and McLellan, Mr. F. J. Lane, and Officers and Engineers of the General Electric Company to discuss the possible causes of the failures of motors and other electrical equipment which had seriously affected the Eastern Region's suburban electric service.

The cause of these failures has not yet been established, but several alternative and possibly complementary theories are being investigated by theoretical analyses, laboratory tests and measurements on equipment in service. In addition a complete train is being equipped as a mobile laboratory to carry out further comprehensive tests. Corrective measures are being developed simultaneously so that appropriate action can be applied as soon as the exact cause has been found. It is not possible at present to predict when these faults can be rectified.

52. I wish to record most appreciatively the great co-operation I have received from all concerned in this Inquiry, particularly from the Officers and Engineers of the British Transport Commission, of the Scottish Region, and of the Associated Electrical Industries Limited. Every facility has been placed at my disposal and everyone has worked unceasingly to ascertain the cause of the serious transformer failures in the Scottish Region and to plan the means of rectifying them. I am particularly indebted to Mr. F. J. Lane, without whose help and advice I could not have completed this interim report. He undertook this investigation at very short notice and he has devoted to it all his energy and all his ability.

53. Finally, in considering this most regrettable closure of a new electric service so shortly after its opening, one must appreciate that the British Transport Commission were breaking fresh ground in the field of electric traction. The Commission pioneered the system of dual high voltage A.C. electrification. Never before had this system been used on any railway. It was applied to multiple-unit trains running on intensive suburban services. Inevitably difficulties arise with such a new system. They were more serious than anticipated and my final report will consider how far they might have been averted. None the less, I am confident that the lessons learned from the failures on the Scottish and Eastern Regions' electrified services will be applied, as necessary, to all electric traction equipment built in Great Britain to ensure that it will be as reliable, as efficient, as safe as any in the world.

I have the honour to be,
Sir,
Your obedient Servant,
**C. A. LANGLEY,**
*Brigadier.*

The Secretary,
Ministry of Transport.

Printed in England and published by
HER MAJESTY'S STATIONERY OFFICE

(89890) Wt. 4111— K16 1/61 D.L.